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Economic Design of Rectangular Water Tank Walls using Parabolic Arches

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Abstract: Rectangular water tanks resting on ground are widely used in water and wastewater treatment plants. These tanks are usually made up of concrete. Discovery of Concrete as a construction material is the most valuable gift to mankind. Concrete behaves as a fluid at the pouring stage & sets within a short interval after pouring. This property of a concrete is valuable & has been exploited to the fullest by the construction industry. However, concrete is weak in taking tensile load thus, requires thicker sections & reinforcement when subjected to tensile stresses. Primary intention of this paper is to overcome this drawback by proposing appropriate geometrical shape to the rectangular concrete water tanks so that the resultant stresses are compressive rather than tensile. This concept is applied to a large water retaining structure.
Keywords: Rectangular Water Tank, Tensile Stresses, Concrete Properties, Parabolic Arch Water Tank, Compressive Stresses

I. INTRODUCTION

Water is considered as the source of every creation and is thus a very crucial element for humans to live a healthy life. Demand for clean and safe drinking water is rising day by day. It has become necessary to store water. Water is stored generally in concrete water tanks and subsequently pumped to different areas to serve the community. Water tanks can be classified as overhead, resting on ground or underground depending on their location. The tanks can be made of steel and/or concrete. Tanks resting on ground are normally circular or rectangular in shape and are used where large quantities of water need to be stored. Overhead water tanks are used to distribute water directly through gravity flow and are normally of smaller capacity. As the overhead water tanks are open to public view, their shape is influenced by the aesthetic view in the surroundings. Water storage tanks are designed as per the provisions of IS 3370. This code was revised in 2009. In the pre revised version, the tanks were designed using working stress method and on the philosophy of no cracking. As per IS 3370:2009, use of the limit state method has been permitted. Hence this study was undertaken to compare the design of rectangular water tank with the proposed parabolic arch tank and to analyze the cost effectiveness in terms of the quantity of steel reinforcement and concrete required.

A. Problem Definition

The threat of global warming is for real and the world as a whole is planning united measures to combat this threat. It has been decided globally that emission of greenhouse gases needs to be controlled and that is where the concept of Carbon Credits has come in. The concept of Carbon Credit is based on a simple premise that those who pollute will have to pay & those who reduce pollution will be rewarded. Thus, if an industry can prove that it has reduced carbon emissions, then it can claim Carbon Credits. Carbon Credits are traded worldwide at $15/credit. The money comes from those who are not in position to reduce carbon emission. Coupled with the above, global water shortage, which has led to compulsive recycling of waste waters & thus for all industries, construction & operation of the waste water treatment plant has become mandatory.

At present, most of the wastewater treatment plants are employing aerobic treatment. Aerobic treatment requires power. As power is produced from coal, any saving in power leads to earning of Carbon Credits. If an existing aerobic wastewater treatment plant can be converted to anaerobic, then, there are two-fold advantages. As aerobic to anaerobic leads to saving power, the cost of new anaerobic treatment plant can come from Carbon Credits. Further, the operational cost will reduce substantially as there is no power requirement. Only hitch, in the above, is that the requirement of storage capacity of treatment tanks in anaerobic process is much larger than aerobic. The treatment units, thus, become costlier & also occupy more space. It is this point that proposed research plans to address. It aims at economical design of large volume, tall concrete tanks. Water retaining rectangular tank of rectangular shape of 30 m x 30 m x 8 m depth is taken as starting point for the study. One of the most popular anaerobic treatment processes is UASB (Up-flow Anaerobic Sludge Blanket). The process requires about 7-8 m of depth for the reactor tank. The fundamental of this process, is that the sludge blanket itself acts as a filter & there is no further power or equipment requirement. It is expected that a large number of UASBs will be constructed in our country. This is the reason for affinity towards choosing a large rectangular tank of 7-8 m depth for study.

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II. METHODOLOGY

A. Conventional Design

In the construction of concrete structures for the storage of liquids, the imperviousness of concrete is an important basic requirement. Aggregates and cement are to be proportioned to yield a high-quality concrete. The permeability of any uniform and thoroughly compacted concrete of given mix proportion is largely dependent on the water cement ratio .While an increase in the water cement ratio leads to an increase in inherent permeability, a highly reduced water cement ratio of a mix with a given cement content may cause compaction difficulties and thus may prove equally harmful. The mix should be designed in such a way that the resulting concrete has a high degree of imperviousness. Honeycombing and segregation of aggregates are to be minimized as these lead to defects which are responsible for leakage in water storage structures.

For a given mix made with particular materials, there is a lower limit to water-cement ratio which can be used economically on any job. It is essential to select a rich mix compatible with available aggregates, whose particle shape and grading have an important bearing on workability which must be suited to the means of compaction selected.

In the following subsection, Conventional design is presented. The vertical wall is designed as a propped cantilever. Propping action at the top of the wall is achieved by a horizontal spanning beam. The beam is in turn supported by a tie beam at every 3 m c/c. The total span of the tie beams which is 30 m, is broken up into 10 span of 3m by providing column grid. These beams are in both perpendicular directions. The supporting columns have independent footings. The wall is provided with independent continuous footing. The bottom raft of the tank is simply slab on grade with nominal thickness of 150 mm. The raft is founded on 100mm thick PCC (plain cement concrete which acts as a levelling course). The General Arrangement drawing showing all the above details along with dimensions is included in the Appendix- I. The quantities & cost of the major civil works are worked out & presented in the following sub-sections.

1) *Design of Tank Wall*

a) Water Depth: 8m
b) Propped Cantilever Moment (negative): 34.13 t-m ($wh^3/l5$)
c) Maximum positive moment : 15.26 t-m ($0.0596*h^3/2$)
d) Thickness Required: 100 cm (based on un-cracked design)
e) Steel Required: Water side vertical: 26.1 cm^2
f) Other side vertical: 13.4 cm^2
g) Horizontal steel: 10 cm^2 (each face)
h) Final Design for Wall: Wall 100 cm at bottom & 30 cm top

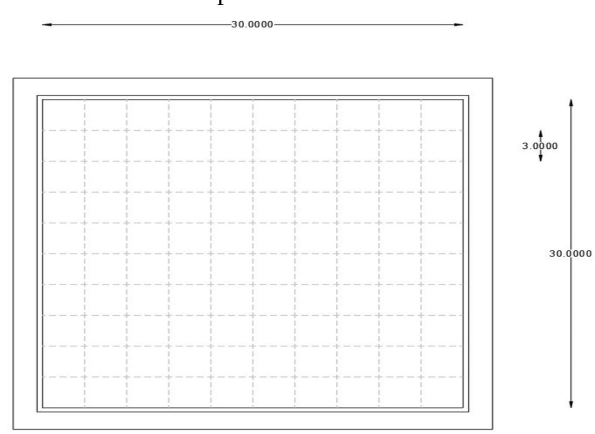

Figure 1 Plan of Conventional Design

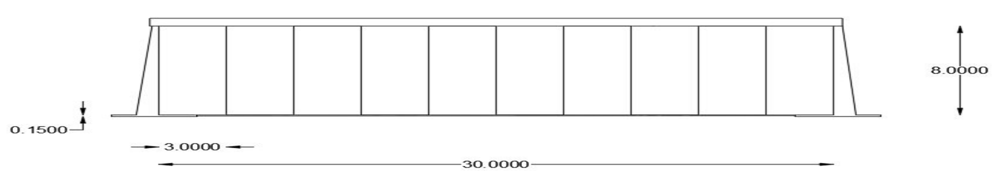

Figure 2 Elevation of water tank by conventional design

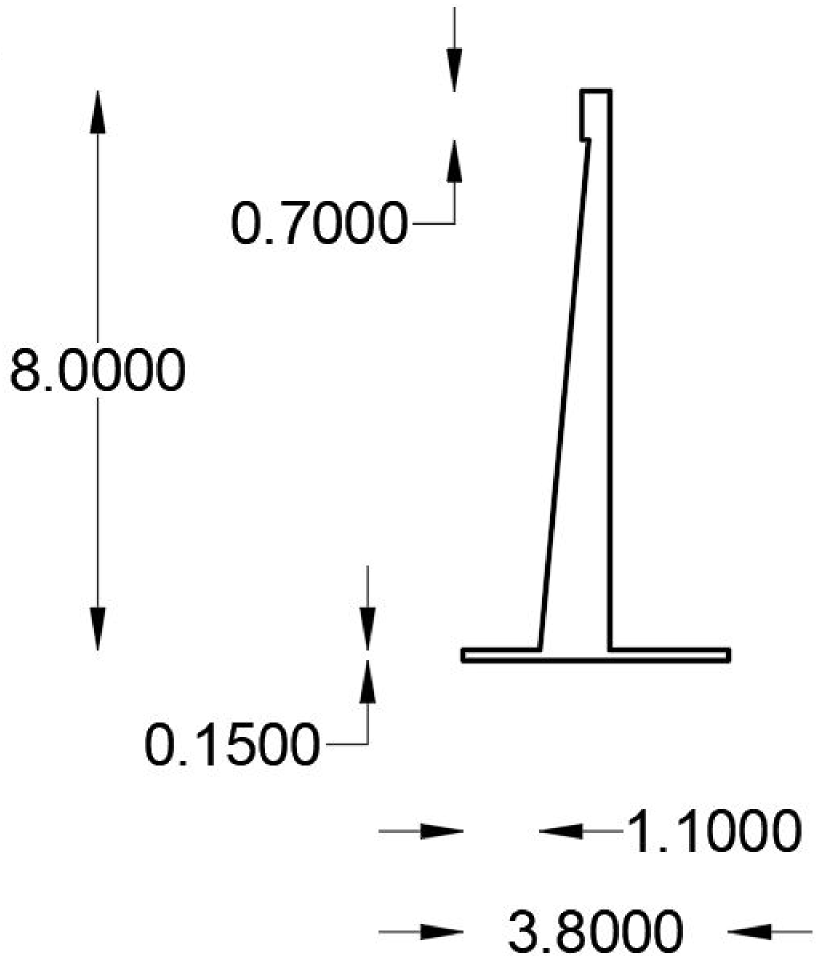

Figure 3 Schematic Representation of Wall

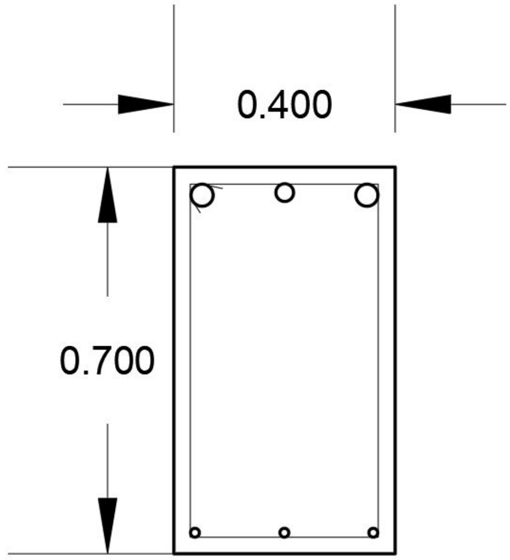

Figure 4 C/S of propping beam

2) *Design of Tank Wall Footing*

Table I Details Of The Footing

Description	Depth(m)	Height (m)	Width (m)	Volume(m^3)	Weight (t)
Rectangular Portion of Wall	0.3	8	1	2.4	6
Triangular Portion of Wall	0.7	8	1	2.8	7
Left Portion of footing	1.1	8	1	-	-
Right Portion of footing	1.7	1	1	-	-
Footing	3.8	1	1	3.8	9.5
Water	1.7	8	1	13.6	13.6
Moment due to water	34.13	-	-	-	-

Calculations (analysis) are as follows:

a) Moment due to rectangular portion of wall (t-m) = -0.3
b) Moment due to triangular portion of wall (t-m) = 2.3
c) Moment due to water = -14.3
d) Total Load, P (t) = 36.10
e) Total Moment, M (t-m) = 21.9
f) Area, A (m^2) = 3.8
g) Section Modulus, Z (m^3) = 2.4
h) P/A (t/m^2) = 9.5
i) M/Z (t/m^2) = 9.1
j) P/A + M/Z (t/m^2) = 18.6
k) P/A – M/Z (t/m^2) = 0.4

Calculations (design) are as follows:

i) Moment on Footing (t/m) = 0.6 (from STAAD)
ii) Depth Required in cm= 13.19

Final Design Of Footing: Thickness: 100 cm, width 3800 cm (1700cm water side & 1100cm other side)

3) *Design of Propping Beam:* This beam is spanning in horizontal direction with supports at every 3m (these supports are provided by tie -frame)

a) Max. Negative Moment at Support = $wl^2/10 = 6.4 \times 3^2 /10 = 5.76$ t-m
b) Use 400 x 700 beam: steel required is 6.44 cm^2.

Final design of Propping Beam : 400 x 700 beam, 2-20 tor + 1- l 6tor (at top) & 3-16(tor at bottom), stirrups 8 tor at l50c/c

4) *Design of Tie Beam:* The beam is primarily subjected to direct tension due to reaction from propping beam. This direct tension is 6.4 x 3 = 19.2 t.

a) Section required = $((19.2 \times 1000)/6)^{1/2}$
b) 600 x 600 cm section is sufficient.
c) Steel required= (19.2 x 1000)/1500 = 12.8 cm^2

5) *Final Design of Tie Beam :* 600 x 600 with 4 bars of 20 tor (top) & 4 bars of 16 tor (bottom) & 8 tor stirrups at 150c/c.

6) *Design Of Columns & Footings:* Columns are required to take only dead loads of beam & self.

a) The load to be taken by each column is (0.6 x 0.6 x 3 x 2 x 2.5) +(0.45 x 0.45 x 8 x 2.5) = 9.5t
b) Column has unsupported length of 8 m.

Final design of Column & footings
450 x 450 cm , 4 -20 tor (top) + 4 -16 tor (bottom) , stirrups 8 tor at 200c/c with
1500 x 1500 x 450 thick sloping footing.

Based on the above design the following quantities are worked out.

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Table II Excavation Quantities

No.	Description	Length (m)	Breadth (m)	Depth (m)	Nos.	Total (m^3)
1	Raft	26.8	26.8	0.3	1	215.47
2	Wall	-	-	-	-	-
3	Wall Footing	29.7	4.1	1.2	4	584.5
4	Internal Column Footing	1.7	1.7	2	81	468.18

Table III Pcc Quantities

No.	Description	Length (m)	Breadth (m)	Depth (m)	Nos.	Total (m^3)
1	Raft	26.8	26.8	0.3	1	215.47
2	Wall	-	-	-	-	-
3	Wall Footing	29.7	4.1	1.2	4	584.5
4	Internal Column Footing	1.7	1.7	2	81	468.18
5	Internal Footing	-	-	-	-	-

Table IV Concrete (M25) Quantities

No.	Description	Length (m)	Breadth (m)	Depth (m)	Nos.	Total (m^3)
1	Raft	26.6	26.6	0.15	1	106.13
2	Wall	31	0.65	8	4	644.8
3	Wall Footing	29.7	3.9	1	4	463.32
4	Top beam	30.7	0.4	0.7	4	34.384
5	Tie b1	31	0.6	0.6	18	200.88
6	Tie b2	-	-	-	-	-
7	Tie b3	-	-	-	-	-
8	Internal column	8	0.45	0.45	81	131.22
9	Internal footings	1.5	1.5	0.45	81	82.013

Table V Plane Shuttering Details

No.	Description	Length (m)	Breadth (m)	Depth (m)	Nos.	Total (m^3)
1	Raft	106.4	1	0.15	1	15.96
2	Wall	31	0.65	16	4	1289.4
3	Wall Footing	29.7	2	1	4	237.6
4	Top beam	30.7	1	1.8	4	221.04
5	Tie b1	31	1.8	1	18	1004.4
6	Tie b2	-	-	-	-	-
7	Tie b3	-	-	-	-	-
8	Internal column	8	1.8	1	81	1166.4
9	Internal footings	6	1	0.45	81	218.70

Table VI Total Quantities And Cost

No.	Description	Total Quantity	Rate(Rs/unit)	Cost (Rs)
1	Excavation	799.97	100	79996.8
2	PCC (M100)	120.53	3000	361596
3	M25 Concrete	1580.74	4200	6639100
4	Plane Shuttering	3935.00	250	983750
5	Curved Shuttering	-	-	-
6	Reinforcement Steel	132.83	58000	7704314

B. Proposed Innovative Design

In the following sub-section, an innovative approach is proposed. The vertical wall is made of a series of parabolic two hinged arches of 3 m span. Thus, in plan on each side, 10 arches are seen. Each arch has a cross section of 1 m x 0.1 m. Bottom. Most arches are designed and the same design is followed till the top of the tank. Property of two hinged parabolic arch is that, both moment & radial shear is zero at every section. Thus, arch needs to be designed for direct compressive force only. Hence, as shown in appendix -2, the 10 cm thickness is sufficient (as against average thickness of 65 cm required in the conventional design). At the arch supports out of the two reactions, reaction along the wall gets cancelled (except for the end arches) while reaction perpendicular to the wall gets added. Columns are provided to cater for these horizontal reactions. The columns are part of frame which extends across the two opposite walls.

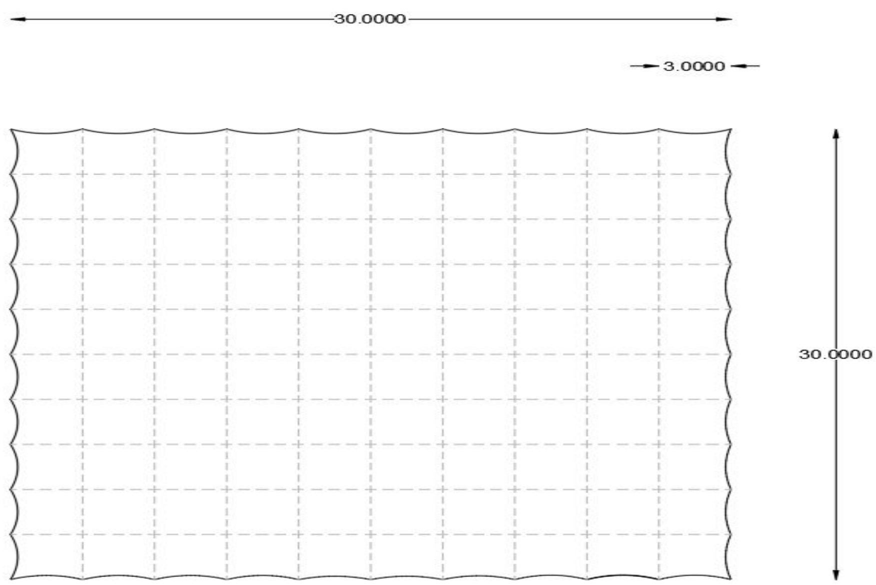

Figure 5 Plan of the proposed design of water tank

It is proposed to use parabolic shape for vertical wall. After number of trials parabolic arch which obeys $y = 0.3 - (4 \times 0.3/3^2)(x - 1.5)^2$ is proposed.

Each arch has span of 3m & rise of 0.3m. On each 30m side there will be 10 such arches. Arches are considered as two hinged arches & thus for uniformly distributed load at any section of the arch moment & radial shear is zero & thus cross section is subjected to only axial compression. Table VII gives the values of axial force at every 0.1 m.

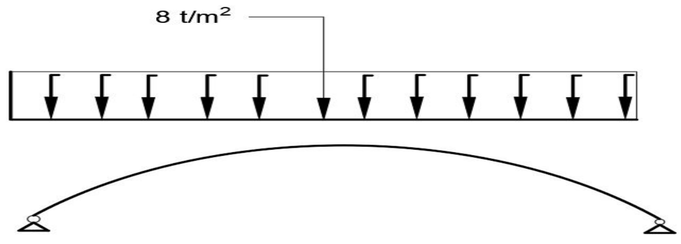

Figure 6 Schematic Loading diagram of the parabolic arch

Table VII Axial Force Values At Every 0.1 M

x	y	tan θ	θ	Sin θ	Cos θ	V(t)	H(t)	Axial Force(t)
0	0	0.40	21.83	0.37	0.9283	12	30.00	32.31
0.1	0.04	0.37	20.50	0.35	0.9367	11.2	30.00	32.02
0.2	0.07	0.35	19.14	0.33	0.9447	10.4	30.00	31.75
0.3	0.11	0.32	17.77	0.31	0.9523	9.6	30.00	31.50
0.4	0.14	0.29	16.37	0.28	0.9595	8.8	30.00	31.26
0.5	0.17	0.27	14.95	0.26	0.9662	8	30.00	31.05
0.6	0.19	0.24	13.51	0.23	0.9723	7.2	30.00	30.85
0.7	0.21	0.21	12.06	0.21	0.9779	6.4	30.00	30.68
0.8	0.23	0.19	10.59	0.18	0.9830	5.6	30.00	30.52
0.9	0.25	0.16	9.10	0.16	0.9874	4.8	30.00	30.38
1	0.27	0.13	7.60	0.13	0.9912	4	30.00	30.27
1.1	0.28	0.11	6.10	0.11	0.9943	3.2	30.00	30.17
1.2	0.29	0.08	4.58	0.08	0.9968	2.4	30.00	30.10
1.3	0.29	0.05	3.06	0.05	0.9986	1.6	30.00	30.04
1.4	0.30	0.03	1.53	0.03	0.9996	0.8	30.00	30.01
1.5	0	0.00	0.00	0.00	1.0000	0	30.00	30.00

In the above table values of Axial Force experienced by the arch section is given. The distributed load w is taken as 8t/m^2 which is at bottom 1 m of the tank.

As can be seen from the above table the maximum axial force experienced by the section is 32.31 t. (The size of the section is 100cm x 10 cm) This gives capacity of 60t (taking M25 concrete).

Thus the 10 cm thickness is more than sufficient to take this compressive load. The gaps created due to arches are filled with lean concrete or brickwork so that the assumed load condition (uniformly distributed) is achieved.

Thus, parabolic arches of 10 cm thick, 3m span & 0.3m rise are provided along the sides of the tank. Thus there are 10 arches per/side adding up to 40 arches for the tank.

At the arch supports out of the two reactions (H & V), reaction along the wall (H) gets cancelled (except for the end arches) while the reaction perpendicular to the wall (V) gets added.

Columns are provided to cater for these horizontal reactions. The columns are made part of frame which extends across the two opposite walls.

Typical such frame is analyzed using STAAD. The input file for STAAD is as following:

```
STAAD PRO
START JOB INFORMATION
ENGINEER DATE 30-0ct-08
END JOB INFORMATION
INPUT WIDTH 79
UNIT METER MTON
JOINT COORDINATES
1 0 0 0; 2 0 2 0; 3 0 4 0; 4 0 8 0;
MEMBER INCIDENCES
1 1 2; 2 2 3; 3 3 4;
DEFINE MATERIAL START
ISOTROPIC CONCRETE
E 2.21467e+006
POISSON 0.17
DENSITY 2.40262
ALPHA 1e-005
```

DAMP 0.05
END DEFINE MATERIAL
MEMBER PROPERTY AMERICAN
1 TO 3 PRIS YD 0.6 ZD 0.3
CONSTANTS
MATERIAL CONCRETE MEMB 1 TO 3
SUPPORTS
I FIXED
2 TO 4 PINNED
LOAD 1 LOAD 1
MEMBER LOAD
1 TRAP GX 24 18 0 2
2 TRAP GX 18 12 0 2
3 TRAP GX 12 0.001 0 4
PERFORM ANALYSIS
FINISH

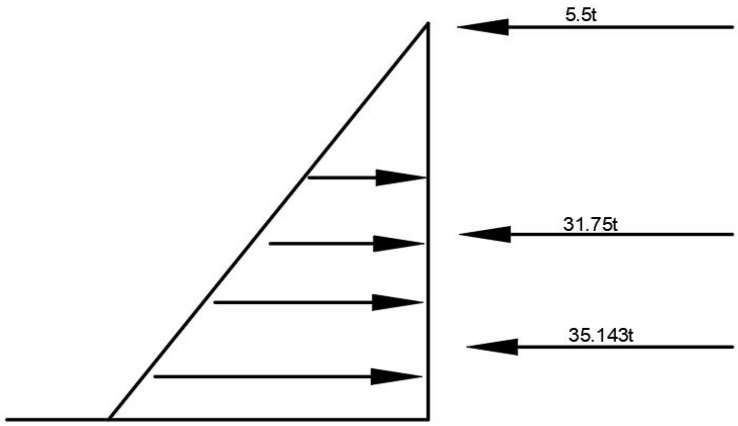

Figure 7 Hydrostatic Static Loading Diagram on Tank Wall

The maximum negative bending moment obtained from the STAAD is 9.83t-m for which the column & footing is designed. The reactions induce tension in tie beams (tie beams are at three levels). Internal columns are only subjected to self-weight.

1) Design of Tie Beam

a) Induced tension = 35.14t

b) Area required= $((35.13 \times 1000)/7)^{1/2}$= 70.84cm x 70.8 cm (M 30 Concrete)

c) Area required= $((31.75 \times 1000)/7)^{1/2}$ = 67.3cm x 67.3cm (M 30 Concrete)

d) Area required= $((5.5 \times 1000)/6)^{1/2}$= 30.3cm x 30.3cm (M 25 Concrete)

Therefore, three sizes adopted for three level tie beams are 75cm x 75cm, 70cm x 70cm & 35cm x 35cm.

2) Design Of Column At The Junction Of Arches

a) M = 9.83 t-m (from STAAD)

b) P= (0.3 x 0.6 x 2.5) x 8 = 3.6 t, say 4t,

c) B= 300mm, D=600mm

d) Pu = 4 x 1.5 = 6t

e) Mu= 9.83 x 1.5 = 14.75t-m

f) Pu/f_{ck} x B x D = 0.0133

g) Mu/ f_{ck} x B x D2 = 0.0546

Refer Chart 44 of IS456 - Design Aid

h) 13.5 cm2 of steel required

Final Design of Column: 300 x 600, 8-16tor & 8 tor stirrups at 200c/c.

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3) Design Of Footing Of Column At The Junction Of Arches

a) Size 1.5m x 2.75m
b) P = 1.5 x 2.75 x 2.5 x 2 = 20.63 t
c) M = 10 t-m
d) Area= 4.13 m^2
e) Z = 1.89 m^2
f) P/A = 5t/m^2
g) M/Z = 5.3 t/m^2

Final Design of Footing: 1.5m x 2.75m x 0.45 m, 10 tor at 150c/c both ways.

Thus, summary of design of various structural elements for this design is as under:

i) *Arch:*100 mm thickness
ii) *Outer Column:* 300mm x 600mm
iii) *Outer Footings:* 1500mm x 2750mm x 450mm
iv) *Internal Columns:* 300mm x 300mm
v) *Internal Footings:* 1250mm x 1250mm x 450mm
vi) *Tie Beam level 1:* 350mm x 350mm
vii) *Tie Beam level 2:* 700mm x 700mm
viii) *Tie Beam level 3:* 750mm x 750mm
ix) Bottom raft thickness -150mm (slab on grade)

Based on the above design the following quantities are worked out.

Table VIII Excavation Quantities

No.	Description	Length (m)	Breadth (m)	Depth (m)	Nos.	Total (m^3)
1	Raft	30	30	0.5	1	450
2	Arch Wall	-	-	-	-	-
3	External Columns	-	-	-	-	-
4	External footings	1.7	3	2.6	44	583.44
5	Internal footings	1.5	1.5	2.6	81	473.85

Table IX PCC Quantites

No.	Description	Length (m)	Breadth (m)	Depth (m)	Nos.	Total (m^3)
1	Raft	30	30	0.1	1	90
2	Arch Wall	-	-	-	-	-
3	Vertical Columns	-	-	-	-	-
4	Footings	1.7	3	0.1	44	22.44
5	Internal footings	1.5	1.5	0.1	81	18.23

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Table X Concrete M25 Quantities

No.	Description	Length (m)	Breadth (m)	Depth (m)	Nos.	Total (m^3)
1	Raft	30	30	0.15	1	135.00
2	Wall	1.1	0.1	8	40	35.2
3	External Columns	8	0.3	0.6	44	63.36
4	External Footings	1.5	2.75	0.45	44	81.675
5	Tie b1	30	0.35	0.35	18	66.15
6	Tie b2	30	0.7	0.7	18	264.6
7	Tie b3	30	0.75	0.75	18	303.75
8	Internal column	8	0.3	0.3	81	58.32
9	Internal footings	1.25	1.25	0.45	81	56.95

Table XI Plane Shuttering Quantities

No.	Description	Length (m)	Breadth (m)	Depth (m)	Nos.	Total (m^3)
1	Raft	120	1	0.15	1	18
2	Wall	-	-	-	-	-
3	External Columns	8	1.8	1	44	633.6
4	External Footings	8.5	1	0.45	44	168.3
5	Tie b1	30	0.75	1	18	405
6	Tie b2	30	0.75	1	18	405
7	Tie b3	30	0.75	1	18	405
8	Internal column	8	1.2	1	81	777.6
9	Internal footings	6	0.45	1	81	218.70

Table XII Total Quantity & Cost

No.	Description	Total	Rate (Rs/unit)	Cost (Rs)
1	Excavation & refiling	1033.44 m^3	100	103344
2	PCC (M100)	112.44 m^3	3000	337320
3	M25 Concrete	1008.06 m^3	4200	4233831
4	Plane Shuttering	2812.50 m^2	250	703125
5	Curved Shuttering	704.00 m^2	1000	704000
6	Reinforcement Steel	81.82 t	58000	4745697
7	Lean concrete	100.00 m^3	2000	200000
TOTAL				11027317

III. RESULTS

Results of both approaches are presented below. In the two tables provided, the quantities & cost obtained from conventional & innovative designs are compared.

All the quantities and the subsequent costs are taken as per current market data.

TABLE XIII
Quantity comparison between conventional and innovative design

No.	Description	Conventional Design	Proposed Innovative Design
1	Excavation	800 m^3	1035 m^3
2	PCC	120 m^3	115 m^3
3	M25 Concrete	1580 m^3	1008 m^3
4	Steel	133 tons	82 tons
5	Plane Shuttering	3940 m^2	2815 m^2
6	Curved Shuttering	-	705 m^2

Table XIV
Cost comparison between conventional and innovative design

No	Description	Conventional Design	Proposed Innovative Design
1	Excavation	Rs.80,000	Rs. 1,03,500
2	PCC	Rs.3,60,000	Rs. 3,45,000
3	M25 Concrete	Rs. 66,36,000	Rs. 42,33,600
4	Steel	Rs. 77,14,000	Rs. 47,56,000
5	Plane Shuttering	Rs. 9,85,000	Rs. 7,37,500
6	Curved Shuttering	-	Rs. 7,05,000
7	Lean Concrete	-	Rs. 2,00,000
	Total	Rs. 1,57,75,000/-	Rs. 1,10,80,600/-

IV. CONCLUSIONS

As presented in Table XIII and Table XIV, use of arches in design of walls leads to a cost reduction of Rs 46,94,400. The innovative design shows a saving of up to 30%. In the new approach, the moment and shear loading was converted to axial compression to utilize the full potential of concrete. A 36% reduction in concrete was observed in the innovative design, which in turn leads to a lower carbon foot print. The results were encouraging as the thickness of wall reduced to 10 cm from average of 65 cm in conventional design. Further, there is scope for thinking on how best to handle the horizontal thrust at the supports of arches. There is scope for trying out capacities and bringing the design to practically adaptable simplicity.

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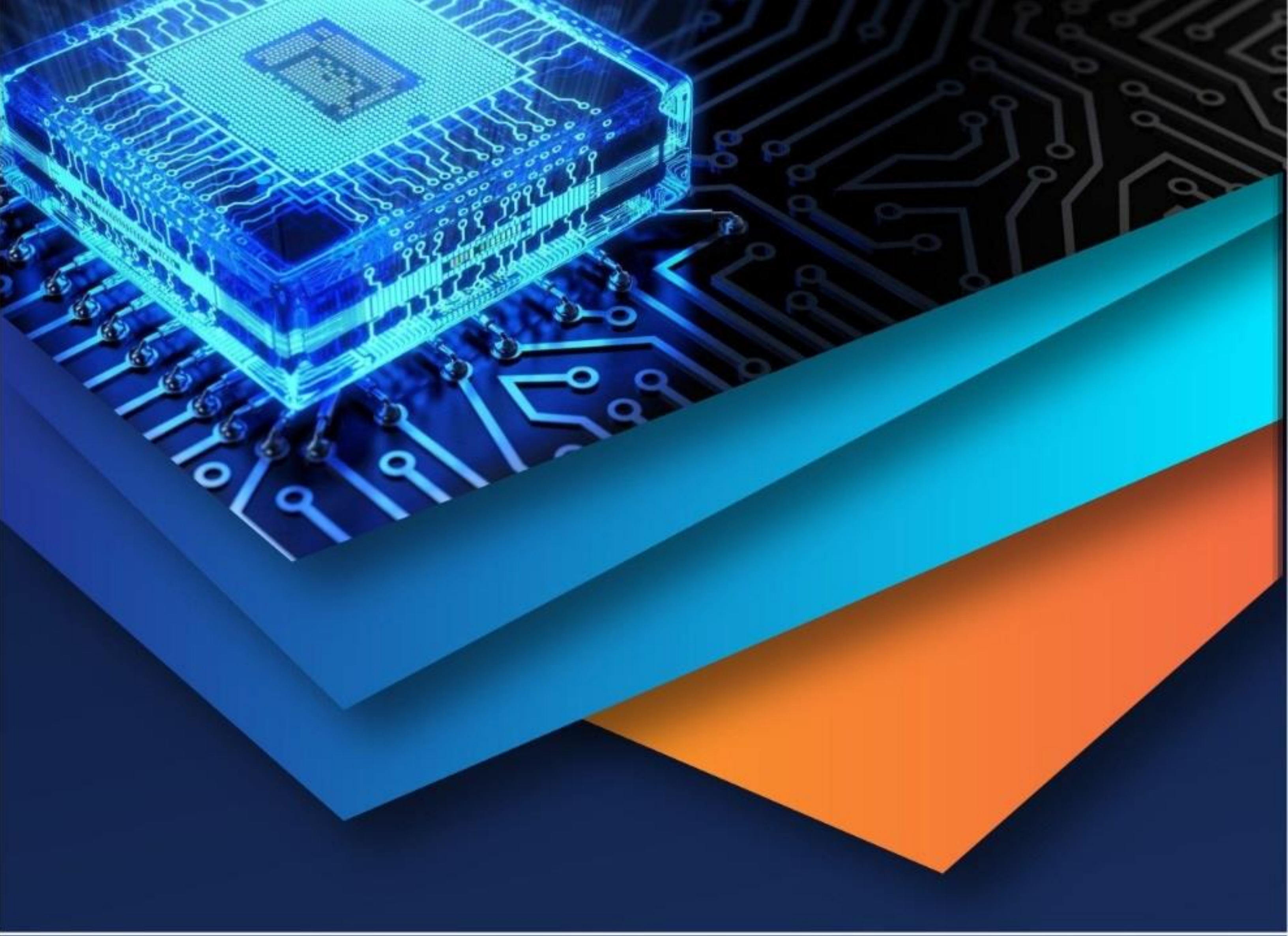

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